Jet Propulsion Laboratory
California Institute of Technology

NASA
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Boundary-Layer Water Vapor Profiling Inside of Clouds Using Differential Absorption Radar

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Scientific motivation

Problem:

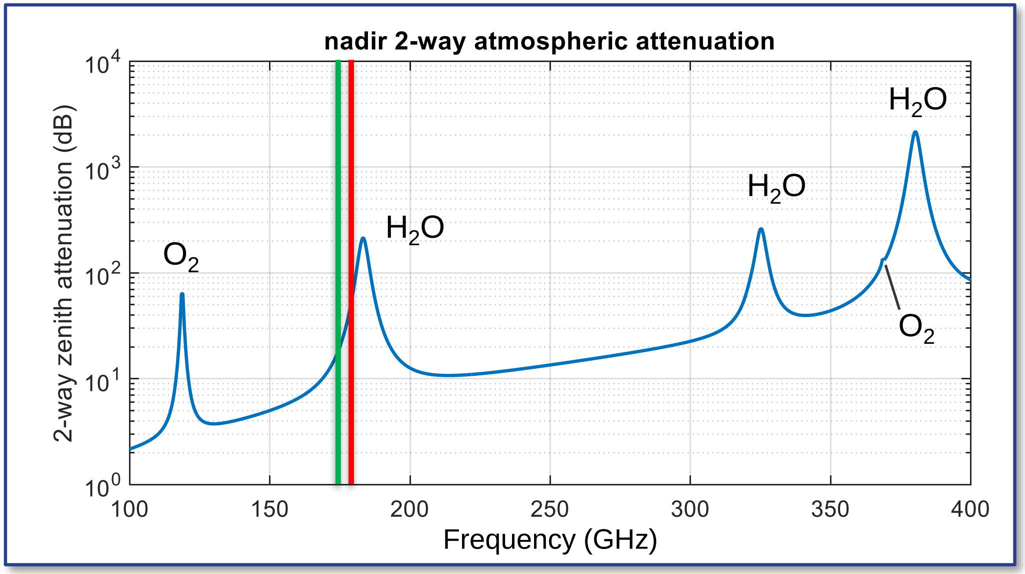
- Existing remote sensing platforms have limited ability to retrieve *high-resolution, unbiased* water vapor profiles in the presence of clouds
- Problem recognized by NWP community (WMO, 2018):

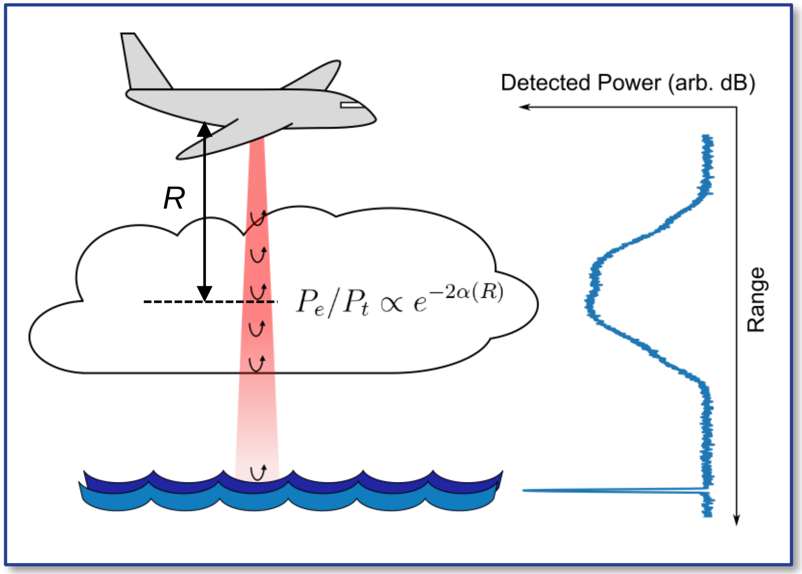
  "Critical atmospheric variables that are **not adequately measured** by current or planned systems are temperature and **humidity profiles** of adequate vertical resolution **in cloudy areas**."

Proposed solution:

- Utilize range-resolved radar signal *and* frequency-dependent attenuation on flank of 183 GHz water vapor absorption line, so-called *differential absorption radar* (DAR)
- Microwave analog of differential absorption lidar (DIAL) – but can measure inside clouds (complementary observations)

Measurement basis





- Differential reflectivity between two closely spaced frequencies proportional to absorbing gas density (integrated)

$$\mathrm{dBZ}(r, f_1) - \mathrm{dBZ}(r, f_2) \propto \int_0^r \rho_{\mathrm{gas}}(r')dr'$$

- *Assumption*: Reflectivity and extinction from hydrometeors independent of frequency
- Frequency dependence from hardware cancels out (common mode)
- Airborne/spaceborne platform ⇒ Surface echoes (total column water)

G-band atmospheric radars

Atmospheric Measurement Techniques
Open Access

G band atmospheric radars: new frontiers in cloud physics

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The present work discusses the potential of G band (frequency between 110 and 300 GHz) Doppler radars in combination with lower frequencies to further improve the retrievals of microphysical properties. Our results show that, thanks to a larger dynamic range in dual-wavelength reflectivity, dual-wavelength attenuation and dual-wavelength Doppler velocity (with respect to a Rayleigh reference), the inclusion of frequencies in the G band can significantly improve current profiling capabilities in three key areas: boundary layer clouds, cirrus and mid-level ice clouds, and precipitating snow.

remote sensing. There have only been a few examples of cloud radars operating at 140–215 GHz in the past (Nemarich et al., 1988; Mead et al., 1989; Wallace, 1988). Such instruments used an extended interaction klystron (EIK), operated as a free running oscillator. The sensitivity was limited as this approach necessitated short pulses, incoherent operation without Doppler and wide receiver bandwidths to accommodate frequency drift. Since the early work of

and Lhermitte (1990) there has been little discussion in the last 20 years on the advantages of radars operating at G band. Today, several of the technological challenges that made the development of radar in G band in the past a risky proposition are now removed thanks to technological breakthroughs (Durden et al., 2011). Thus, it is timely to revisit the topic of the potential applications of G band radars in cloud research. Here, we state their added value in cloud research when operated in ground-based super-sites complementing existing cloud radar facilities. G band radars could be potentially

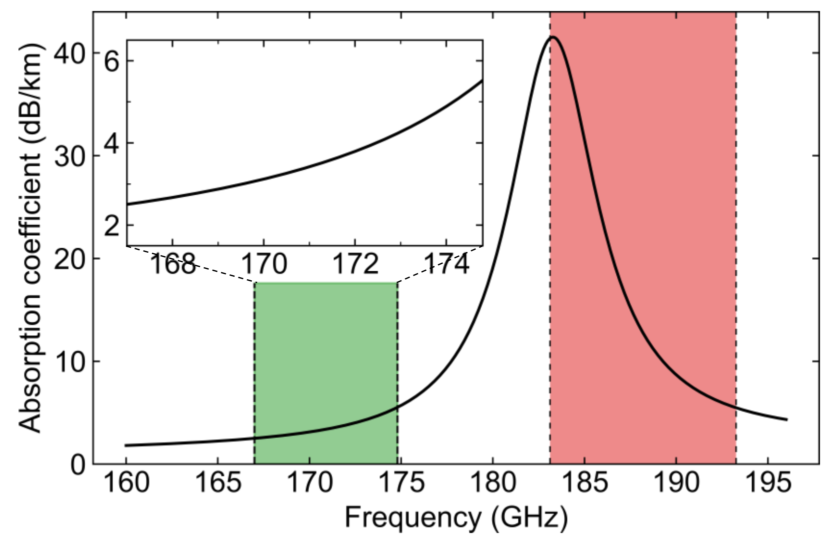
A. Battaglia *et al.*, Atmos. Meas. Tech., 7, 1527-1546, https://doi.org/10.5194/amt-7-1527-2014, 2014.

The vapor in-cloud profiling radar (VIPR)

VIPR

- NASA ESTO Instrument Incubator Program (IIP)
- Tunable across 167 to 174.8 GHz band
- Achievable transmit power < 1 W ⇒ **FMCW mode of operation**
- Ground deployments for validation at Scripps Institute of Oceanography and DOE SGP ARM
- Demonstration flights on Twin Otter in 2019

VIPR frequency band

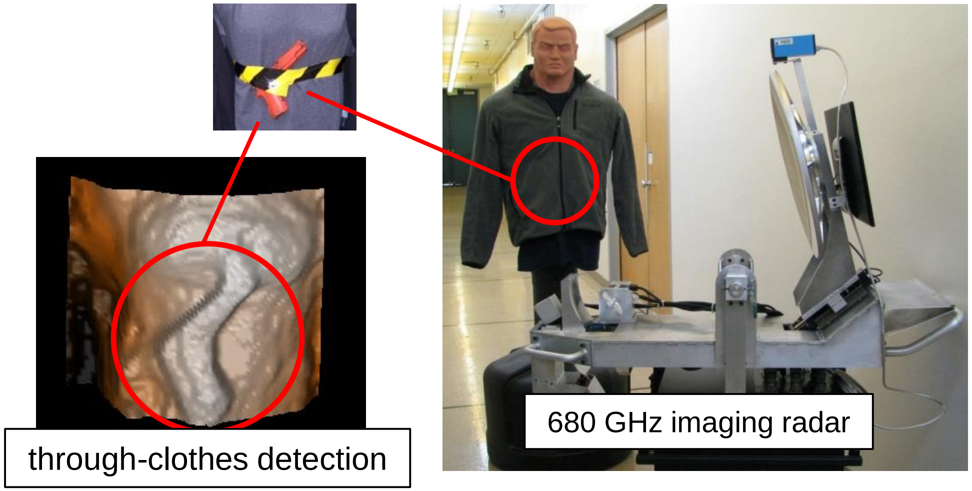


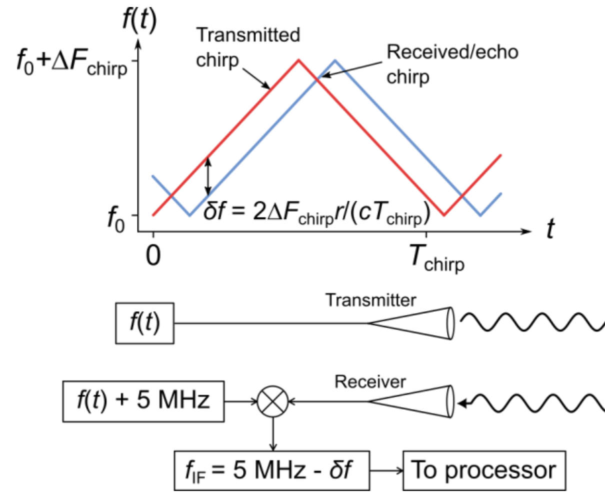
- Sensitivity to upper-tropospheric water vapor (ice clouds)
- Strong attenuation in planetary boundary layer (PBL)
- Transmission prohibited (passive sensors)

- Lower absolute absorption ⇒ sensitivity to PBL water vapor
- Profiling (PBL clouds/precipitation) and total column water measurement capabilities
- Fewer transmission restrictions

Instrument heritage at JPL

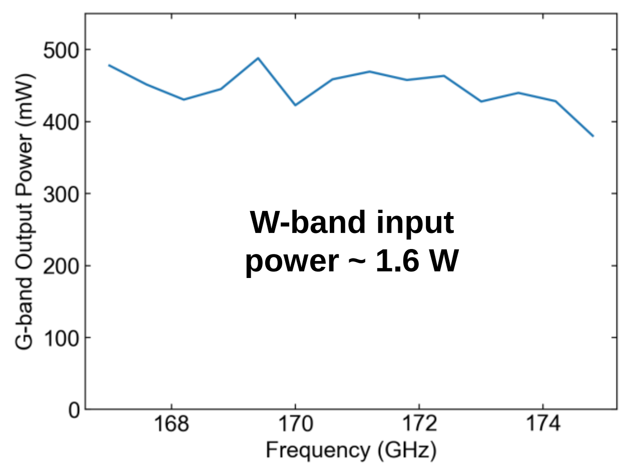
Frequency-modulated continuous-wave (FMCW) radar for security imaging

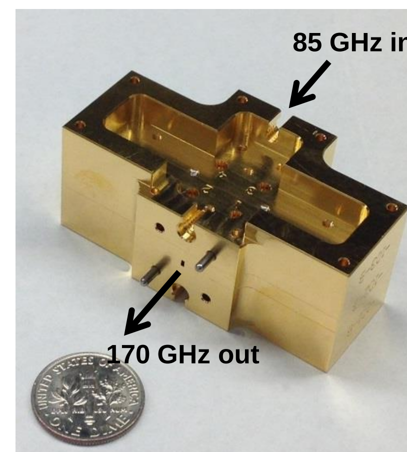




- Extensive THz FMCW radar R&D at JPL for security imaging applications
- NASA ESTO funded effort for high-power solid-state sources near 183 GHz
- State-of-the-art InP low-noise amplifiers developed for millimeter-wave radiometry and heterodyne spectroscopy

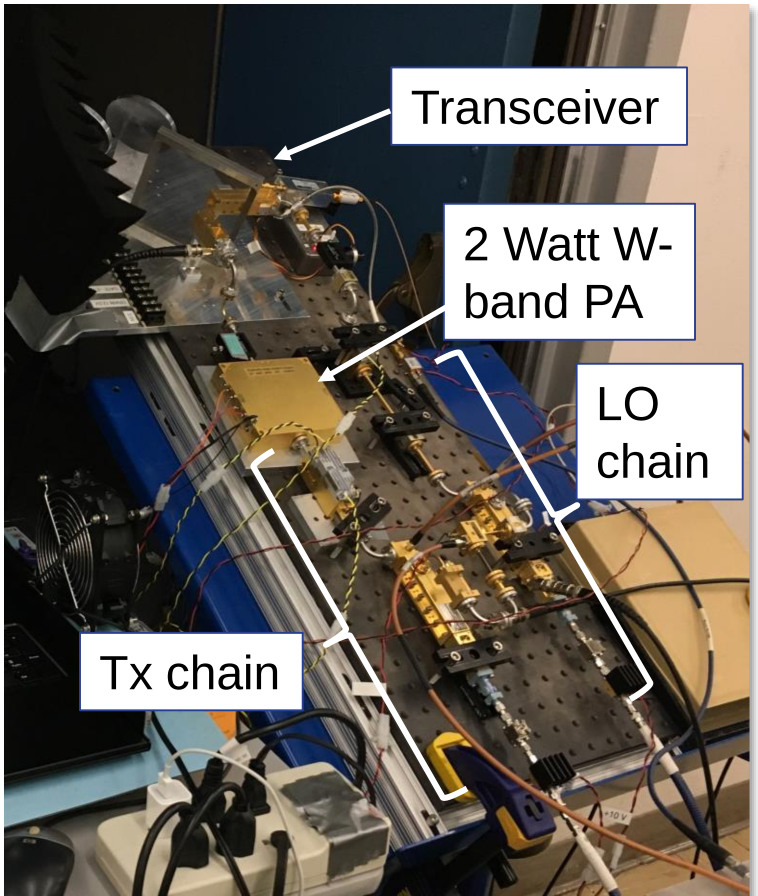
Record output power G-band sources



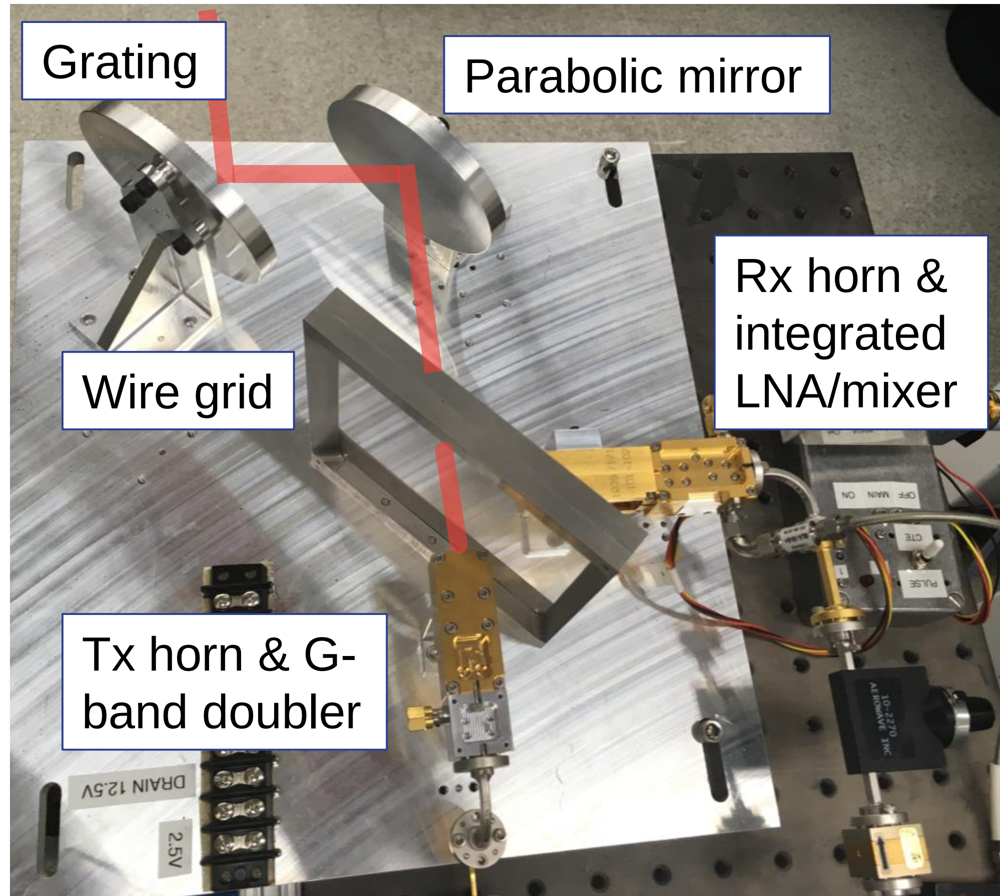


Ground testing setup

Radar front end



Transceiver



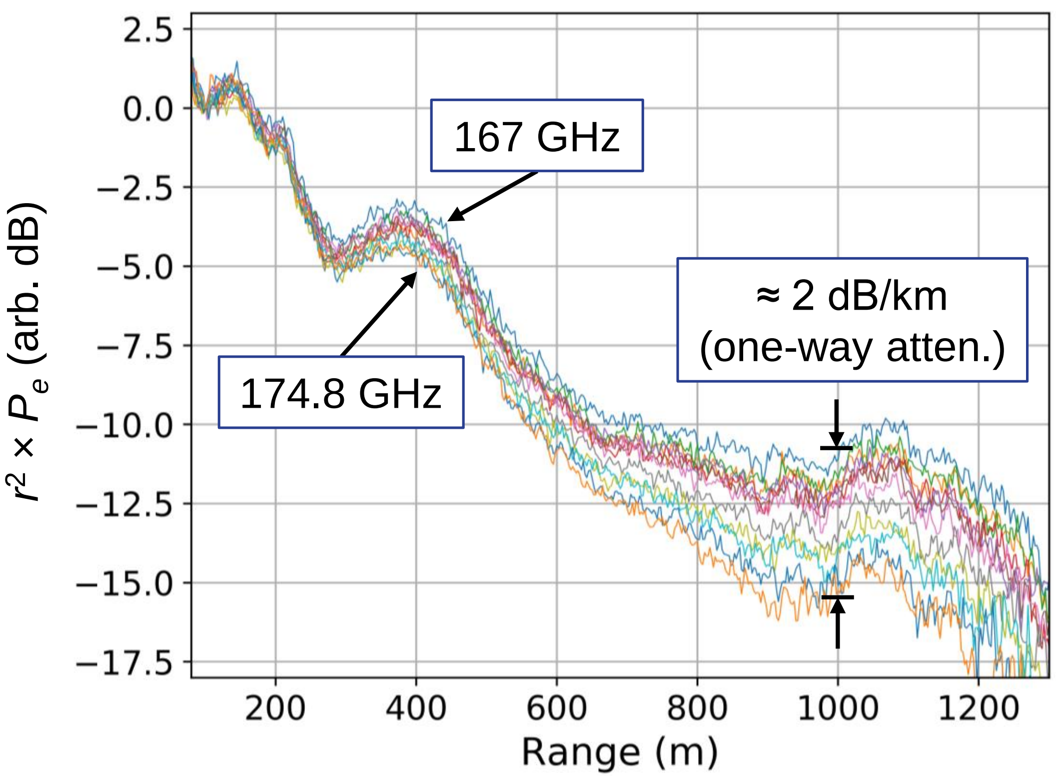
- 100 mW Tx power
- 40 dB antenna gain

Values for initial testing

Rain/cloud field tests @ JPL

Precipitating clouds

Power spectra normalized to values at 100 m



Reflectivity

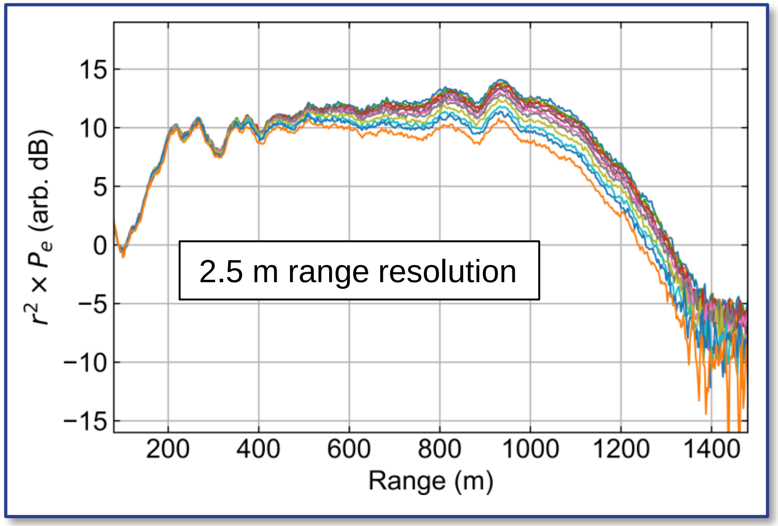
Optical depth

$$r^2 P_e(r, f) \propto Z(r) e^{-2\alpha(r,f)}$$

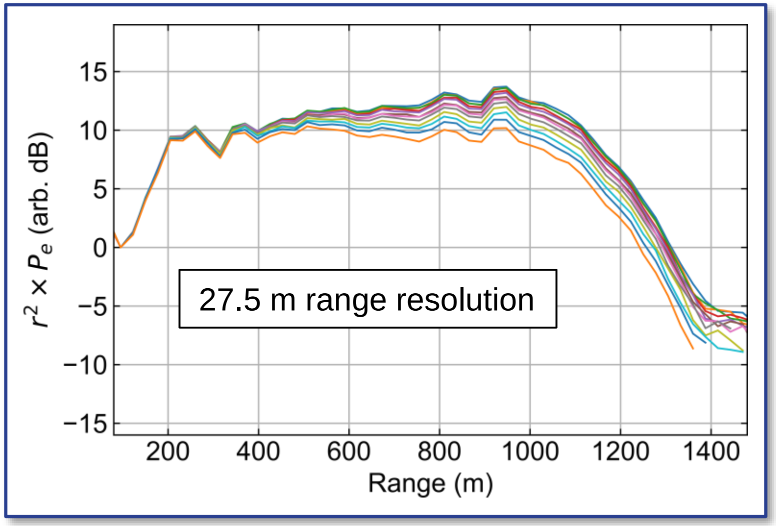
Radar parameters:

- Radar pointing 30° above horizontal
- N = 2000 pulses at each of 12 Tx frequencies
- Pulse (i.e. chirp) time of 1 ms
- Total meas. time = 25 sec

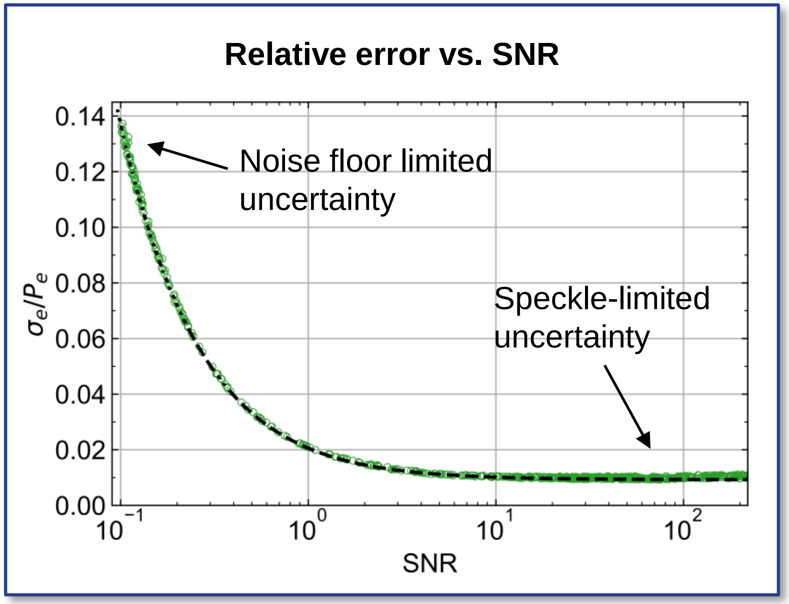
DAR signal processing



Bin (i.e. downsample) radar spectra by factor of 10 to reduce statistical uncertainty



- Measurement error agrees very well with statistical model based on radar speckle noise



R. Roy *et al*. *Atmos. Meas. Tech.*, 11, 6511-6523 (2018)

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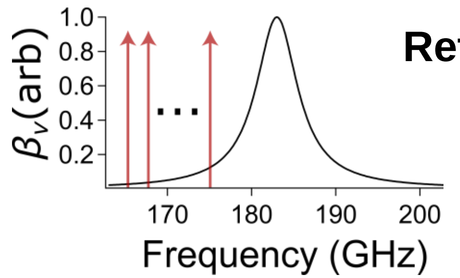
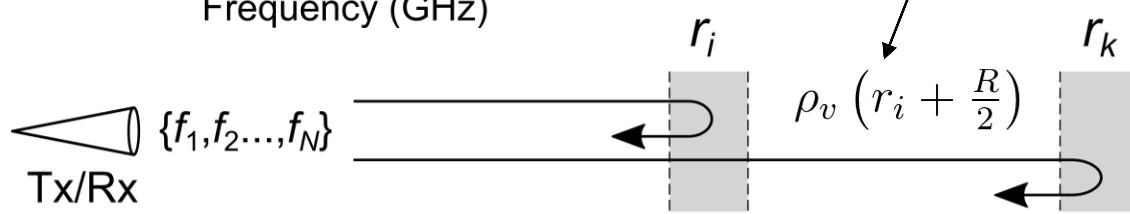
Humidity retrieval

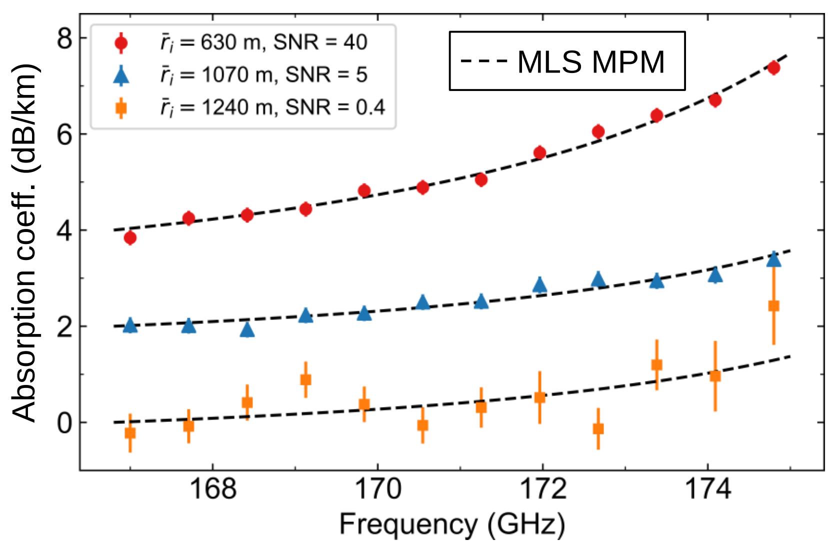
- Fit millimeter-wave propagation model to measured absorption coefficient $\beta_v(f)$ to extract humidity

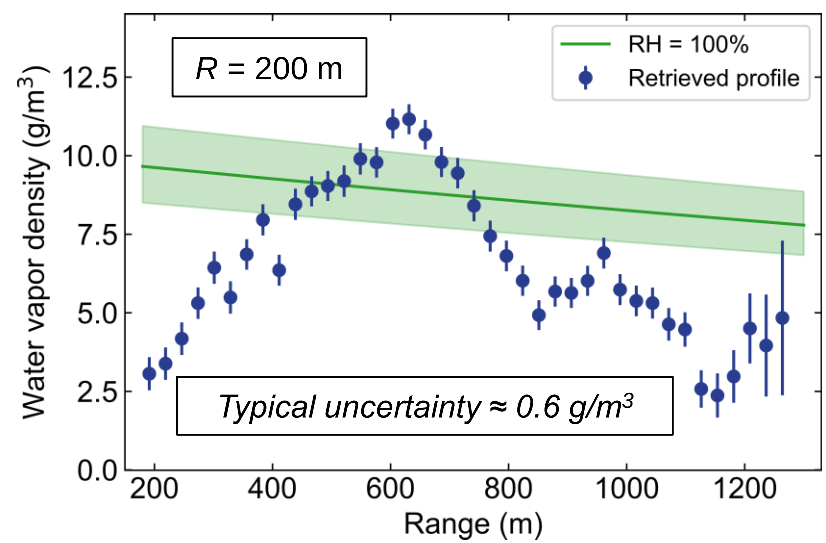


Retrieval step size: $r_k - r_i = R$

$$\beta_{\text{meas}} = \frac{-1}{2R} \ln\left(\frac{P_e(r_i + R, f)}{P_e(r_i, f)}\right)$$







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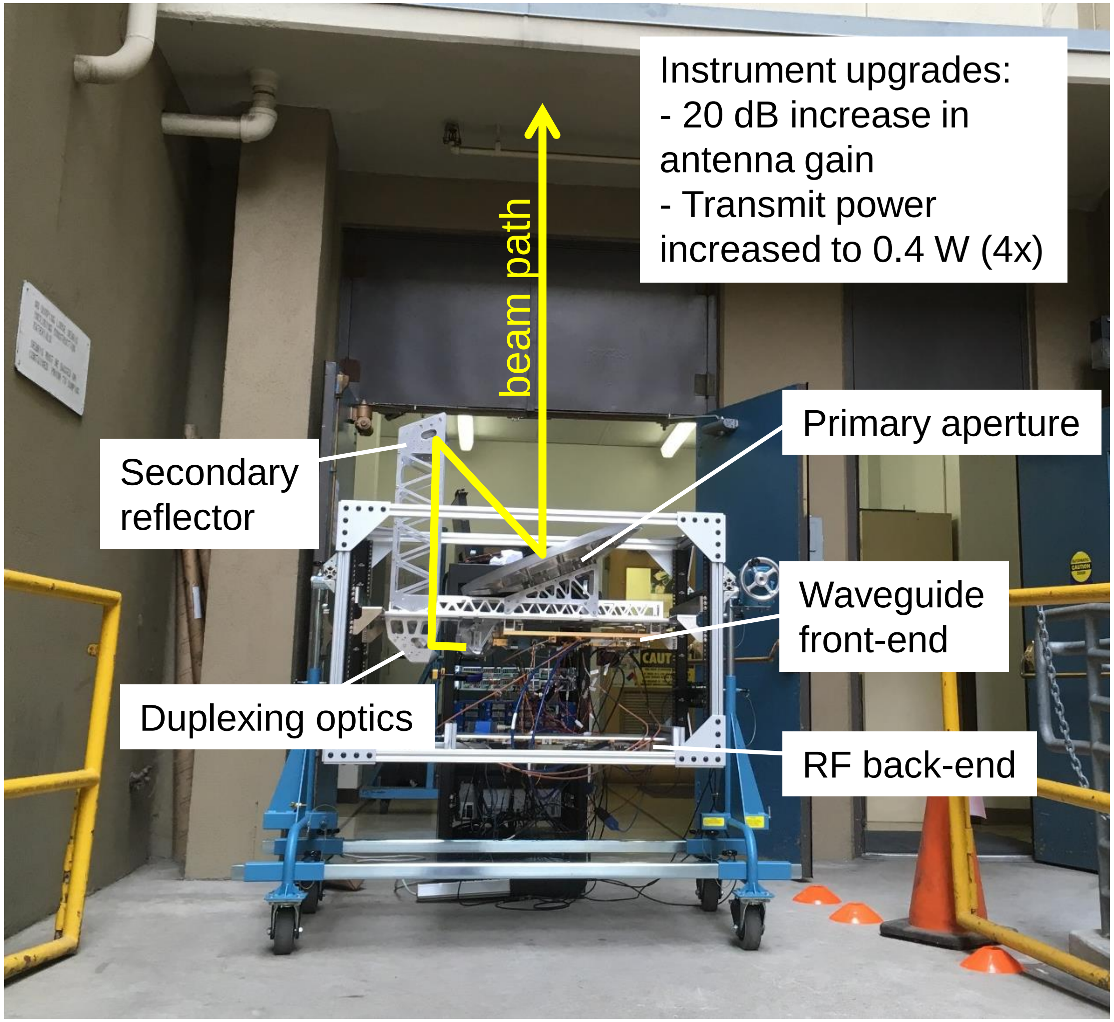
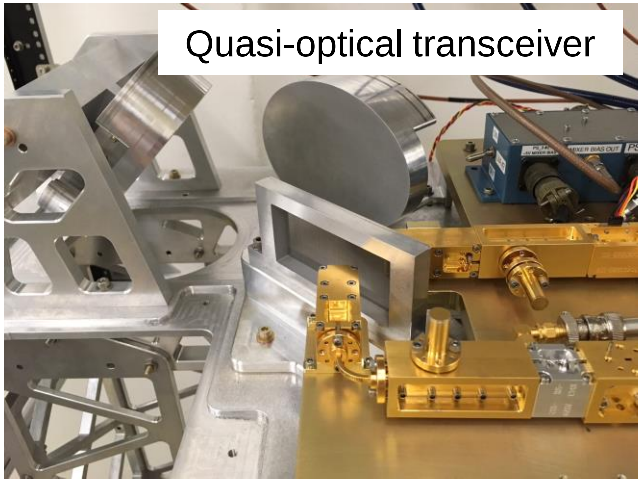
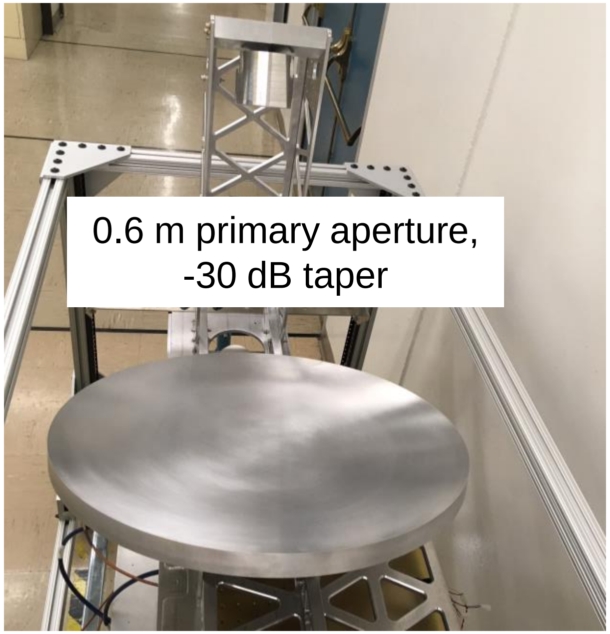
Toward airborne deployment

Airborne compatible VIPR system on Flotron rotation stage

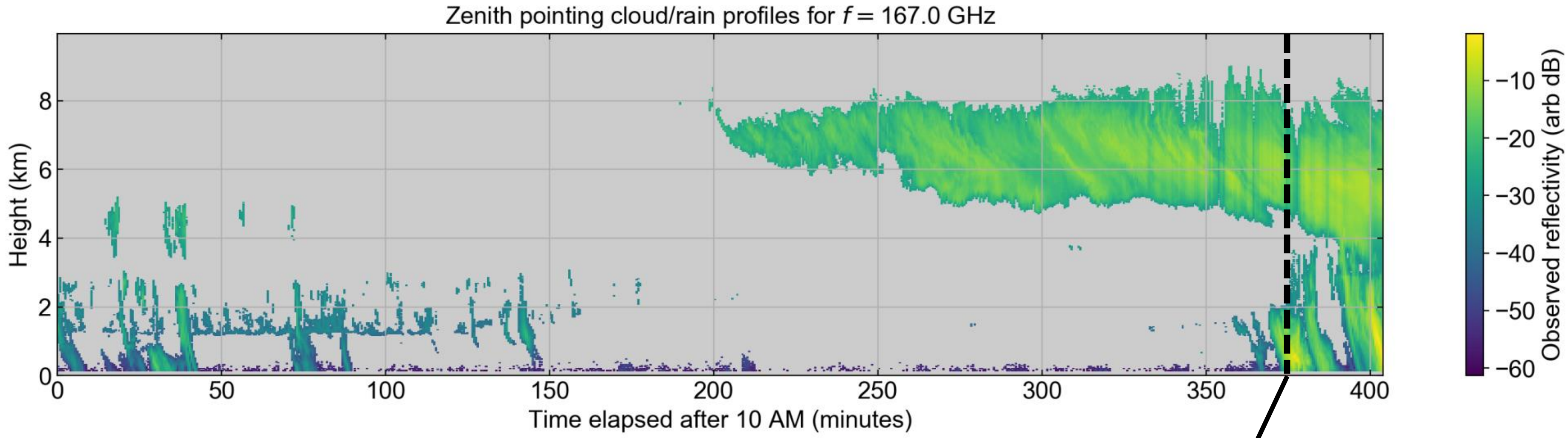


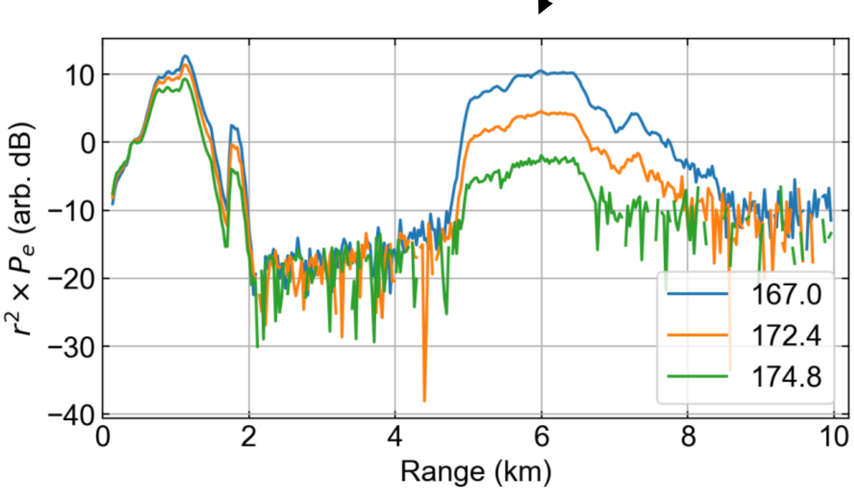




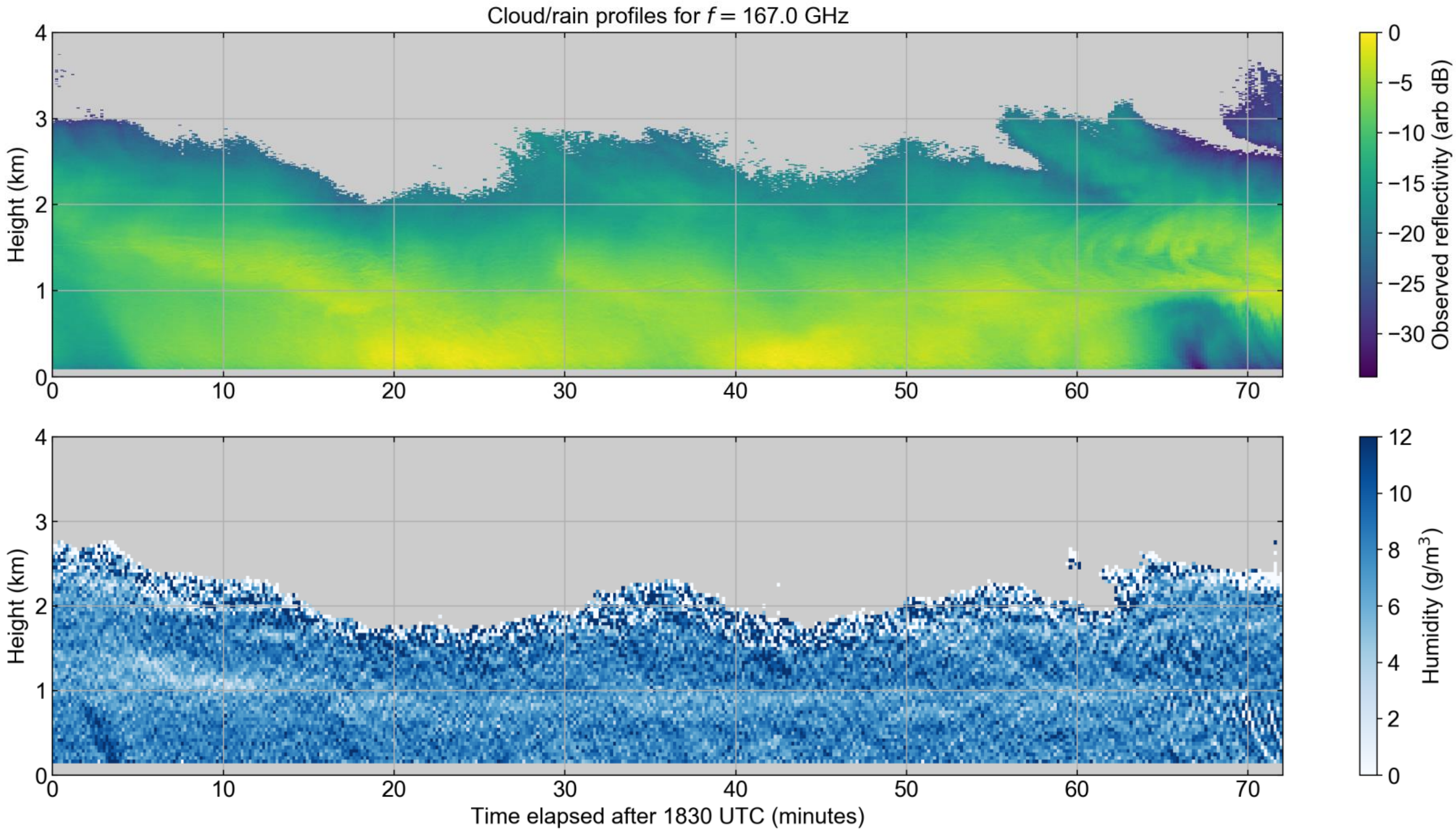
Increased radar sensitivity

October 3, 2018 @ JPL – Clouds detected beyond 8 km in height





Deployment of VIPR at Scripps in collaboration with the Center for Western Weather and Water Extremes (Radiosonde validation) – Dec. 5, 2018



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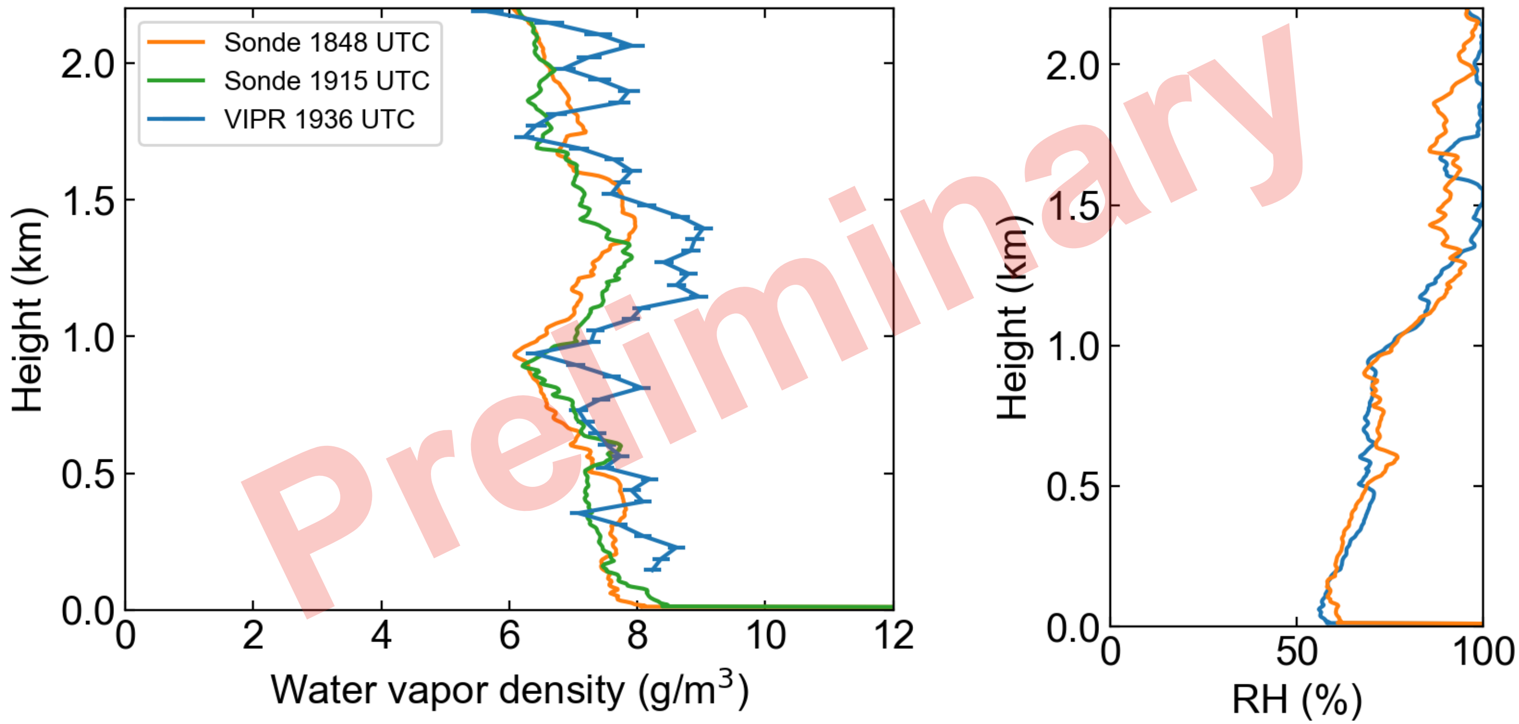

Conclusions and outlook

Past and present:

- G-Band differential absorption radar proof-of-concept instrument assembled and preliminary field testing successful
- First in new generation of solid-state G-band cloud radars
- Humidity retrieval algorithm implemented, yielding profiles with 200 m resolution and high-SNR precision of 0.6 g/m^3 (R. Roy *et al*. *Atmos. Meas. Tech.* 2018)
- Deployment of aircraft-compatible system at Scripps for validation – analysis currently ongoing

Future outlook and prospects for space:

- Aircraft deployment and investigation of total column water measurements
- Humidity profiling from space with order 100 W transmitter (technical challenge)
- Lower power transmitter (1-10 W) can perform TCWV measurements with **ubiquitous temporal, surface, and cloud coverage**
- Opportunity for upper-tropospheric humidity sounding using the strong water vapor line at 380 GHz

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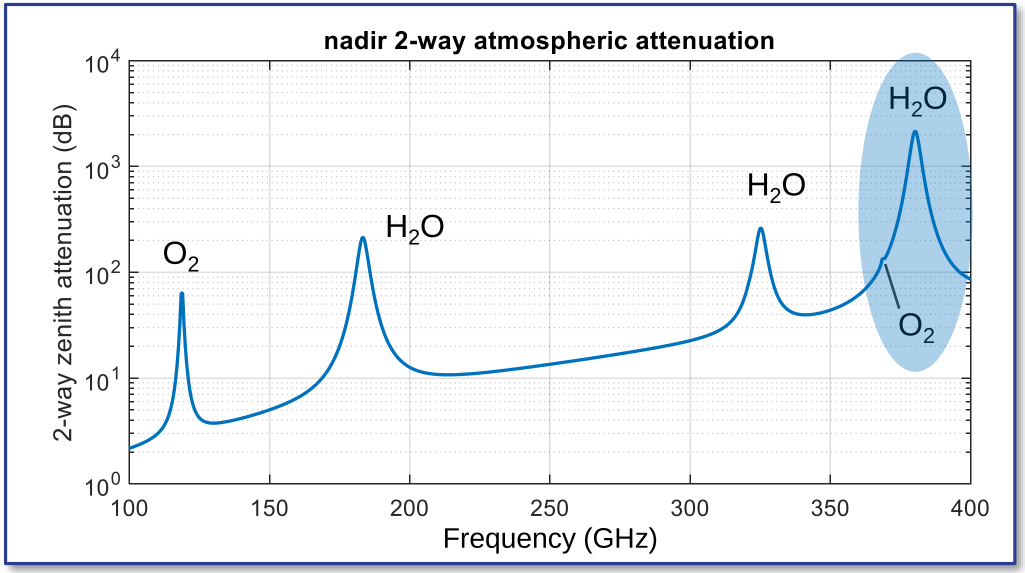
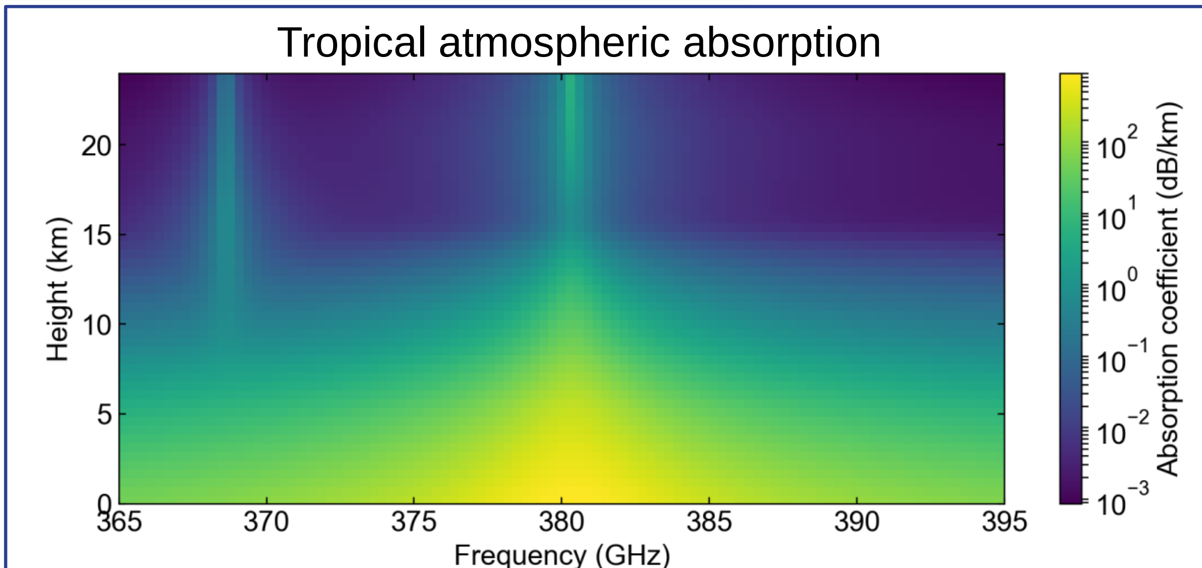
380 GHz DAR humidity sounding



- No transmission restrictions
- Primary sensitivity to upper-tropospheric water vapor
- Proximity of O_2 line opens possibility for simultaneous temperature sounding
- Example application: profile humidity in deep convection anvil outflow



Thank you for your attention

Questions?

Thank you to NASA ESTO for funding the project.

Systematic bias considerations

Retrieved humidity

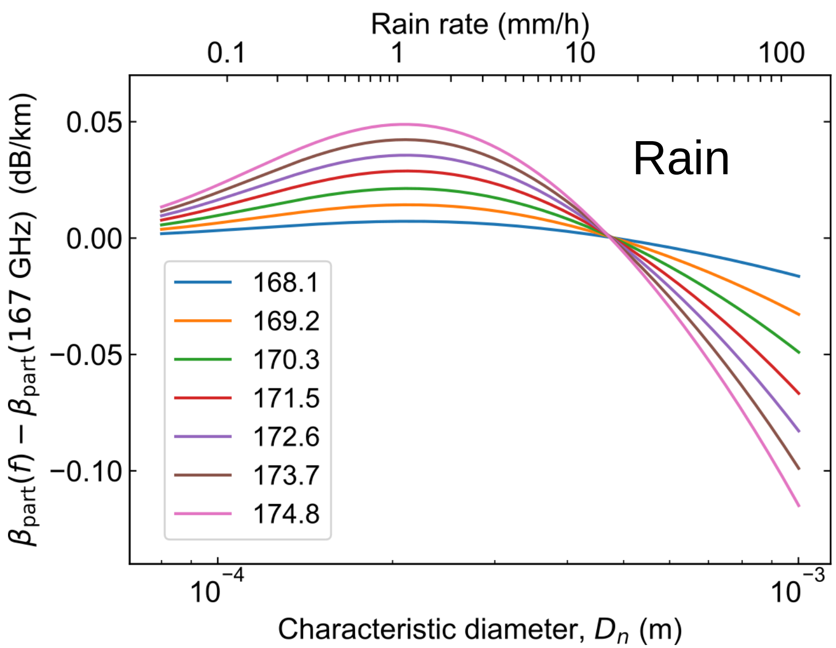
Actual humidity

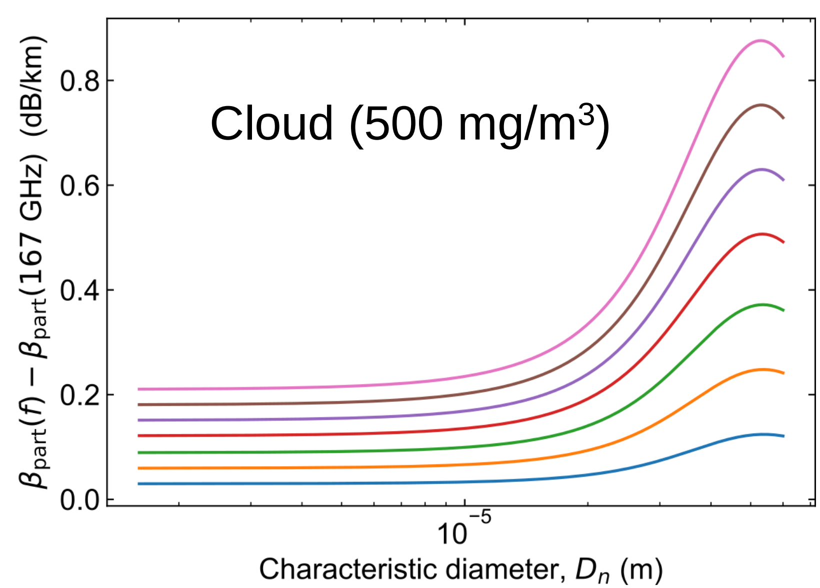
Reflectivity bias

Particulate extinction bias

$$\tilde{\rho} = \rho + \frac{1}{2\underbrace{\Delta\kappa}_{\text{Differential mass extinction coefficient} \approx 0.3\ \text{dB/km/(g/m}^3\text{)}}R}\left[\ln\left(\frac{Z(r_2, f_1)}{Z(r_2, f_2)}\right) - \ln\left(\frac{Z(r_1, f_1)}{Z(r_1, f_2)}\right)\right] + \frac{\Delta\beta_p}{\Delta\kappa}$$

Differential mass extinction coefficient ≈ 0.3 dB/km/(g/m^3)





Connection to the Decadal Survey

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated	Explorer	Incubation
Clouds, Convection, and Precipitation	**Coupled cloud-precipitation state and dynamics** for monitoring global hydrological cycle and understanding contributing processes including cloud feedback	Radar(s), with multi-frequency passive microwave and sub-mm radiometer	X		
Atmospheric Winds	**3D winds in troposphere/PBL** for transport of pollutants/carbon/aerosol and water vapor, wind energy, cloud dynamics and convection, and large-scale circulation	Active sensing (lidar, radar, scatterometer); or passive imagery or radiometry-based atmos. motion vectors (AMVs) tracking; or lidar**		X	X
Planetary Boundary Layer	**Diurnal 3D PBL thermodynamic properties and 2D PBL structure** to understand the impact of PBL processes on weather and AQ through high vertical and temporal profiling of PBL temperature, moisture and heights	Microwave, hyperspectral IR sounder(s) (e.g., in geo or small sat constellation), GPS radio occultation for diurnal PBL temperature and humidity and heights; water vapor profiling DIAL lidar; and lidar** for PBL height			X
Surface Topography and Vegetation	**High-resolution global topography** including bare surface land topography ice topography, vegetation structure, and shallow water bathymetry	Radar; or lidar**			X

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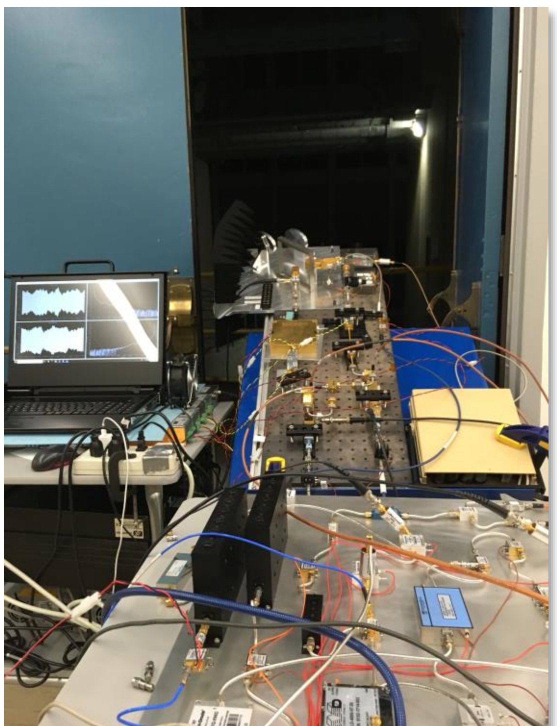
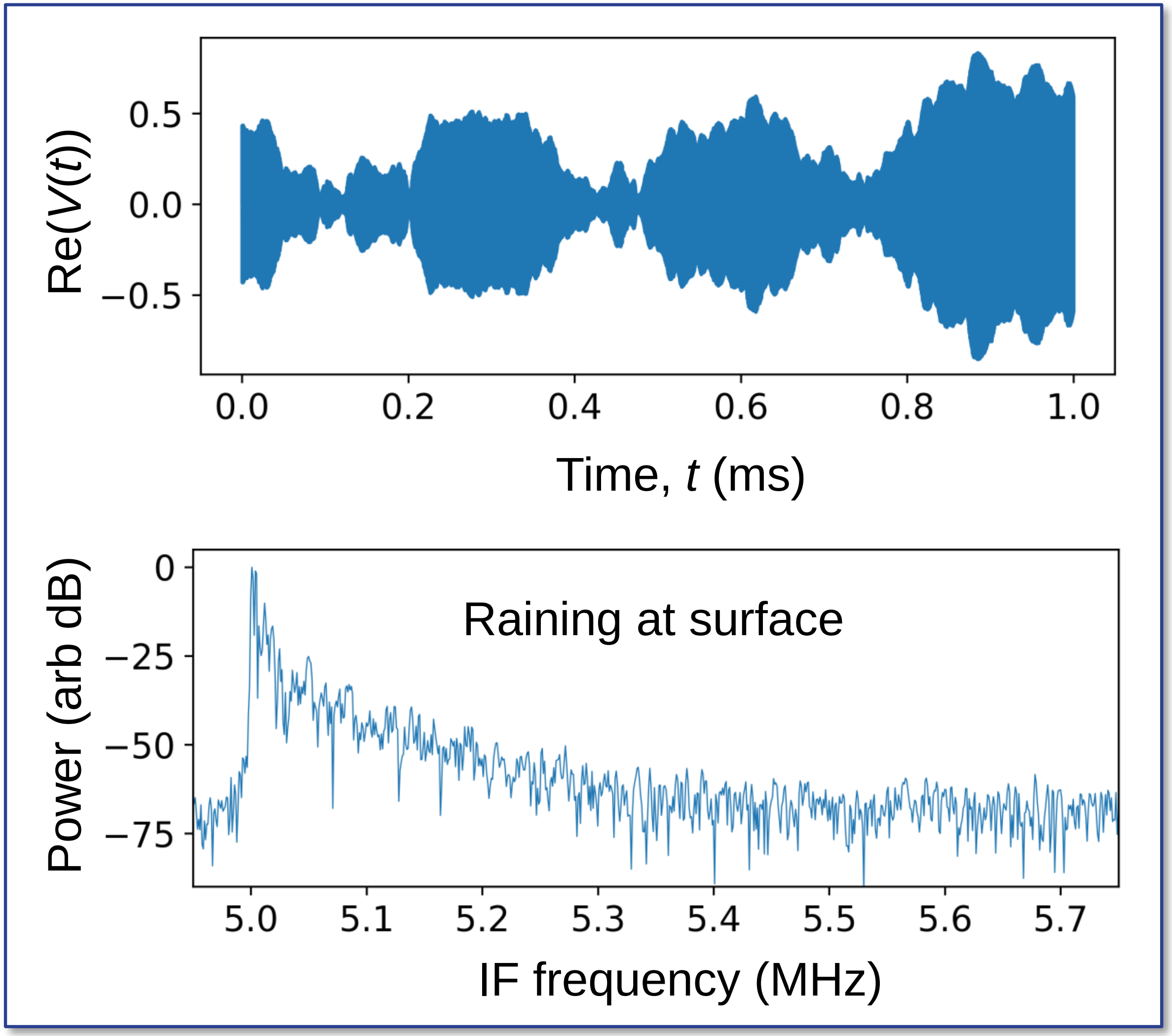
Rain/cloud field tests @ JPL

- Radar pointing 30° above horizontal
- N = 2000 chirps (1 ms) at each of 12 Tx frequencies
- Total meas. time = 25 sec

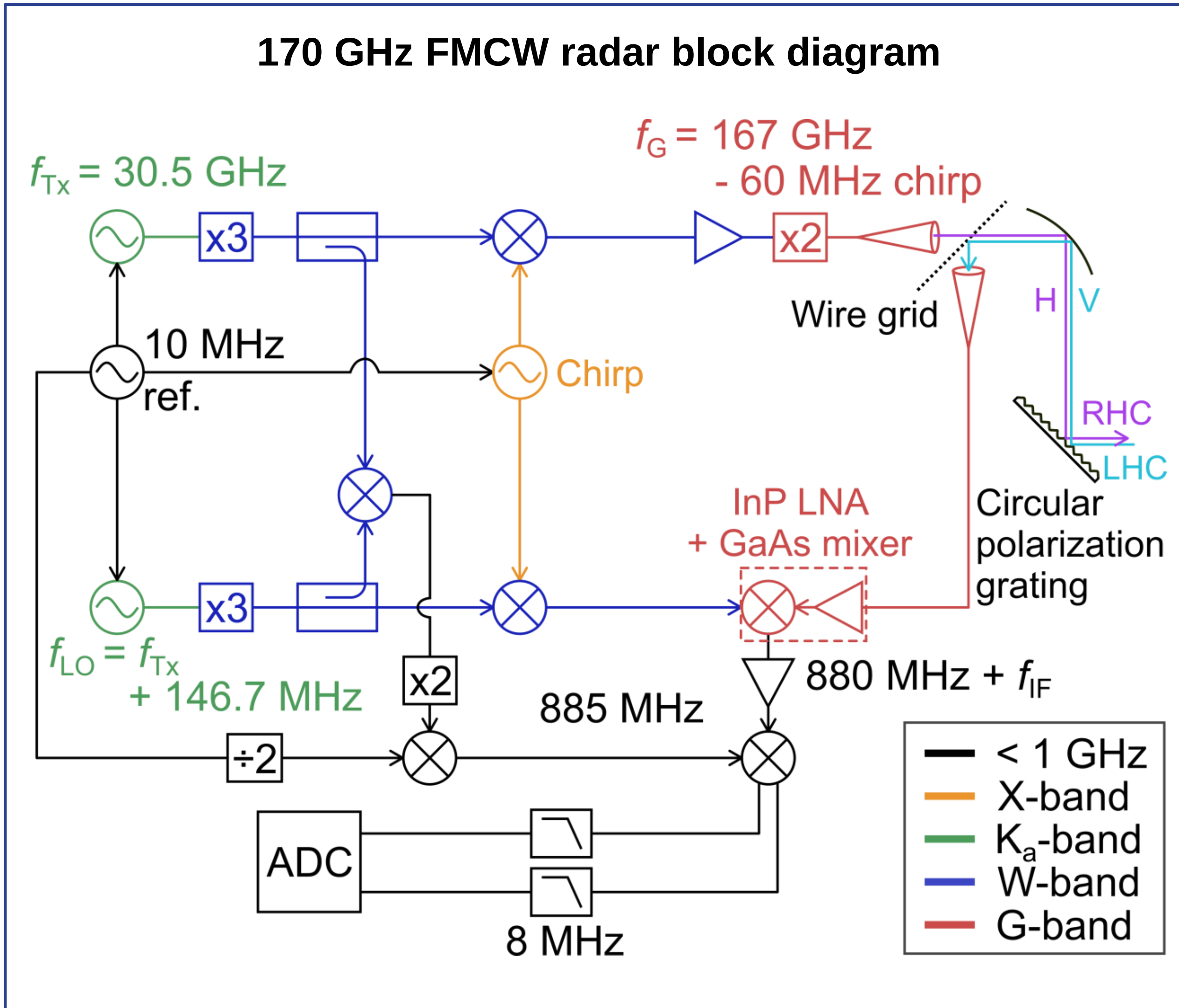


Downwards chirp



VIPR architecture

- Transmitter tunable from 167 to 174.8 GHz
- Nominal range resolution 2.5 m (60 MHz chirp bandwidth)
- Very high quasi-optical isolation permits simultaneous operation of Tx/Rx **and** single common aperture
- Oscillator phase-noise cancellation (homodyne) techniques enable thermal-noise-limited detection



Background noise floor considerations

- Differential measurement derived from ratio of *radar echo power* at two different ranges:

$$\frac{P_e(r_2,f)}{P_e(r_1,f)} \propto e^{-2\alpha(r_1,r_2,f)}, \quad \alpha(r_1,r_2,f) \propto \int_{r_1}^{r_2} \rho(r')dr'$$

One-way optical depth

- But the power we detect is the sum of the echo power *plus* the background noise power:

$$P_d(r,f) = P_e(r,f) + P_n(r,f)$$

- Note:

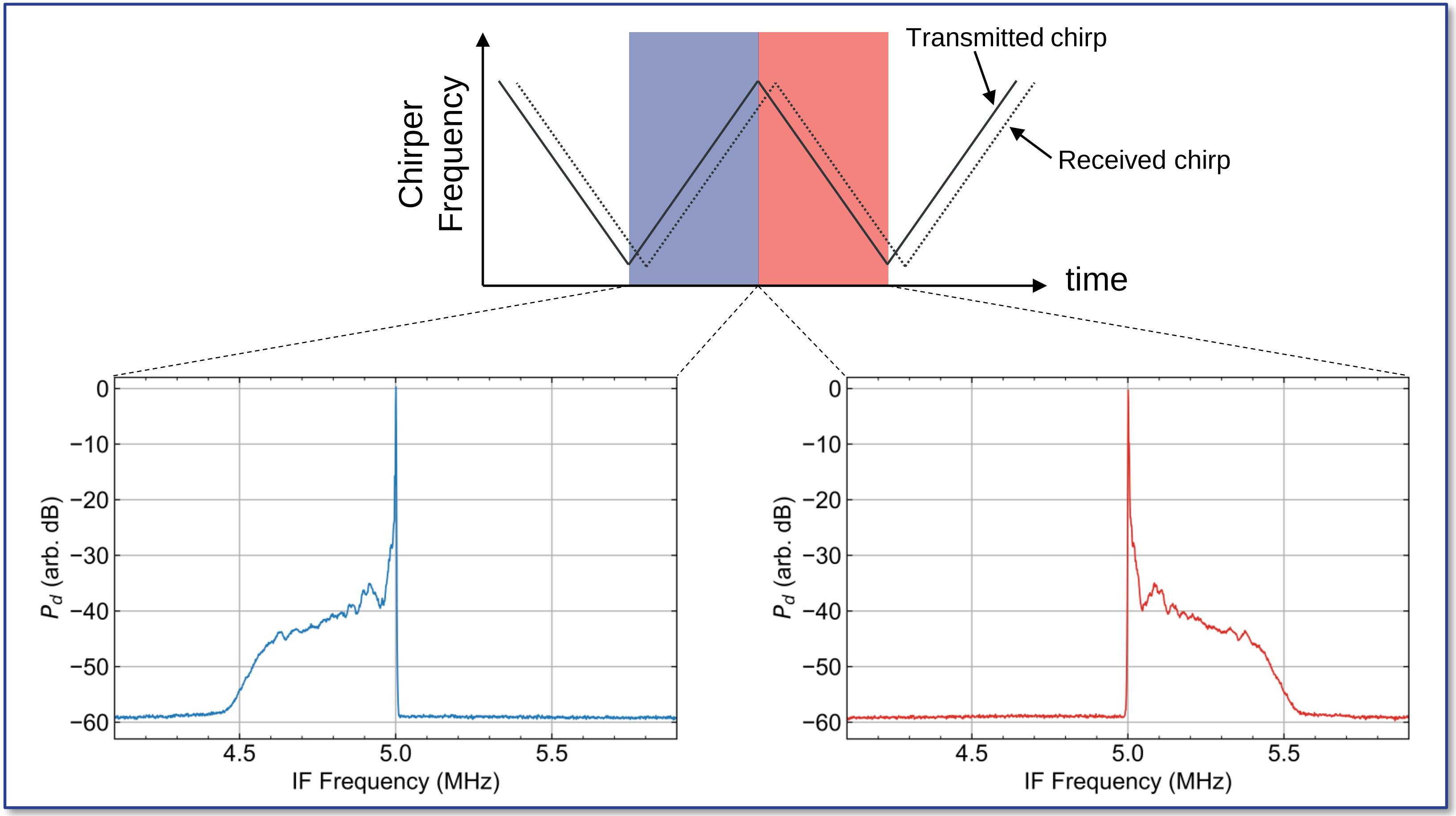
$$P_n(r,f) \neq \text{constant}$$

  - Ripple in the radar IF spectrum
  - Changing scene brightness temperature

⇒ have to acquire and subtract true background noise floor – otherwise clear low-humidity bias for low-SNR

Real-time noise floor subtraction

— Acquire cloud/rain signal spectrum **and** background noise floor simultaneously by using bidirectional chirp (triangle wave)



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